Monitoring human body motions during earthquakes

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MONITORING HUMAN BODY MOTIONS DURING EARTHQUAKES

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ABSTRACT

This work aims at establishing laboratory requirements and testing conditions in order to understand the physical and emotional stability of people during a ground shaking. Several individuals with different human characteristics (gender, age, height, etc.) are considered in the test. Two different laboratory setups are presented. A position device (Kinect) and video targetless tracking algorithm has been used to collect the human body position during the shaking. A two and a three dimensional shaking tables are used to generate artificial earthquakes with different frequency bands. In addition, a well detailed virtual reality setting is applied to the testing site in order to illustrate the real environment. During the experiment, a special attention has been given to the factor of "surprise", which is necessary to ensure a natural reaction of the individuals. The result of the experiment proved common behaviors among the individual samples during the shaking. This work is considered a first step towards a large test campaign, which is necessary to obtain comprehensive statistics on this topic.

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Introduction

The number of casualties caused by an earthquake is usually linked to the damage inside structures during the event. While the human losses is positively correlated to the structural damage, injuries have also been found to occur even when no damage was present in the main structural components. Such injuries are the result of the individuals being struck by objects or falling off the staircase while trying to escape from the building. Therefore, the human reaction to shaking itself is also an important component for injuries and death during earthquakes. Test on humans

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due to vibration has been performed in different areas of knowledge [1, 2]. In the literature, the only experiments, to our knowledge, that focus on human behavior during seismic shaking conditions were performed in [3-9], which proved that human actions are limited by physical and emotional reactions during seismic events. As an example Takahashi in [3, 4] used a shaking table to reproduce floor motion during an earthquake and then measure the performance of human actions and people feelings (anxiety, panic, etc.). The inputs of the shaking table were sine waves and their combination were chosen to be as close as possible to floor response of different building to tremors.

This paper aims at understanding the ability of normal people to maintain their position during ground shaking by exposing them to an artificial earthquake using a shaking table. People involved in this experiment were both male and female. All of them were equipped with protectors for head, elbows and knees. The time history movements of their head, chest, belly, elbows, knees and toes have been recorded using a position device (Kinect). A two dimensional shaking table is used to generate artificial earthquakes. In addition, a virtual reality setting has been created in order to achieve a more realistic environment. During the experiment, special attention was given to the factor of “surprise” to ensure a natural reaction by the individuals. At the end of the test all participants were asked to fill a questionnaire regarding their impressions and feelings whose result is also presented in the paper.

Facilities and Equipment

The research groups at Politecnico di Torino and University of Chile perform complementary test. Laboratory facilities are described below.

Politecnico di Torino

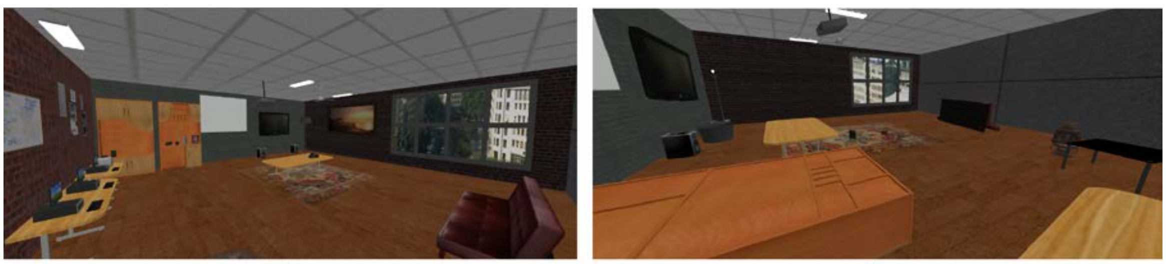
Virtual Reality

The growing investment by Google, Facebook, Microsoft, HTC and Sony in Virtual Reality demonstrates that this technology is a reliable solution for many aspects such as training, testing and researches. Virtual Reality has been used for years in medicine as surgery training, for motor rehabilitation and psychological treatments. Professional and free of charge developing environment such as Unity 3D, open source modelling software as Blender, relative low cost virtual reality head mounted display like Google Cardboard or Samsung Gear VR and user tracking/natural interaction sensor like Microsoft Kinect allows the uses of synthetic environment a research opportunity within the reach of any university.

The virtual reality system that has been developed in this research is a client-server application that uses the following hardware equipment:

- Samsung Gear VR 2016;
- Samsung Galaxy S8;
- Microsoft Kinect V2 Sensor.

The software has been developed using Unity3D for the client side, and C# with Kinect V2 SDK for the server side. The simulation system has to achieve three goals: quick development time, cost-efficient software/hardware architecture, connection between one's movements in real world and those perceived into the virtual environment. For this reason, a smartphone-based head mounted display is used to reduce realization costs: the Samsung Gear VR in conjunction with Samsung S8 android smartphone represents a good compromise among costs, computational resources and scalability. It allows the user to move his visual field along all the degrees of freedom. Two virtual environments - indoor and outdoor - have been developed in Unity 3D using mesh modelled with Blender and several free available Unity assets (Figs. 1a and 2). The virtual environment runs on Samsung S8. The spatial variability of the earthquake motion is reproduced by three sinusoidal temporal histories with random amplitude applied in the three directions. When the virtual environment is shaken every object in the scene is affected and moves in accordance with the input signal: paintings fall off the wall, furniture tilts and overturn (Fig. 1b). In addition, sound effects are used to increase the realism and the emotional response of the user. Microsoft Kinect sensor allows the system to track the user position along the 3 translational degrees of freedom. The user position is transmitted to the virtual environment by control software via Wi-Fi using a text-based message protocol. The transport layer protocol chosen is TCP. The control software is developed using C# and Kinect SDK, as it allows to choose which virtual environment to load, to define the maximum displacement and the duration of the experiment.



(a) (b)

Figure 1. Virtual indoor environment before (a) and after the earthquake (b).

Figure 2. Virtual outdoor environment.

Shaking Table

A two degree of freedom shaking table has been used for the tests described in this article. It is driven by linear electric actuators, as they are more responsive for high velocities and low loads. Moreover, a modular design has been adopted in order to be quite versatile according to the needs. In this case the configuration provided consists in two adjacent steel tracks connected each other by steel profiles. The tracks are 3 m long and the sections’ size is 40x100x4 mm. They are also provided with aluminium guides, which allow two carriages to move along the longitudinal direction. Each track has its own carriage that consists in a 600x500x10 mm aluminium platform and is moved by an actuator anchored to the underneath structure. Upon this plate, another actuator is fixed along the transversal direction as well as another track with a mobile aluminium platform of the same size on top. The two small platform are located at a certain distance along the longitudinal direction so that a bigger platform (1500x1500x10 mm) can fit upon them (Fig. 3). The two longitudinal actuators have a maximum stroke of 510 mm, a peak force of 1020 N and a maximum velocity of 2.0 m/s. The other two, instead, have a maximum stroke of 330 mm, a peak force of 858 N and a maximum velocity of 1.6 m/s. A specific software, provided by the manufacturer of the actuators, has been used to configure control parameters of the motors so that the system can effectively recreate the input signal. Control and data acquisition are performed through an embedded device provided with analog and digital I/O lines, an accelerometer and a FPGA. Also, it has an USB port which has been used to connect a pen drive containing the input files. A specific code has been written to handle both sending and acquisition phases, including tasks such as setting sample rates, comparing, generating and scaling signals.

Figure 3. Shaking table at Politecnico di Torino.

University of Chile

Shaking Table

The shaking table used at Universidad de Chile has six degrees of freedom. A 2x2 m platform structure was set up for the tested individual (Fig. 4).

Figure 4. Shaking table testing system at University of Chile.

For safety reason the testing area was surrounded by a rail covered with flexible polyethylene foam. Additionally, individuals used a harness to prevent abrupt collapse due to the motions. The table is capable of reproducing acceleration in the order of 0.6 g and rotations up to 23 degrees. Maximum payload of the system is 1000 kg. Other table nominal capacities are described in Table 1. These conditions limits the testing of individuals to environments were the predominant motions are on the low frequency side of the spectrum, in practical terms this corresponds to people inside structures were the predominant motions are below 5 Hz and the acceleration are below 0.6 g. One of the main benefit of this table is the possibility to reproduce rotations and vertical motions components that add a more realistic environment to the tested individual.

Table 1. Motion system main features.

Degree of Freedom	Displacement Comb. Motion	Displacement Single DOF	Velocity	Acceleration
Pitch	±22 deg	±21 deg	±30 deg/s	±500 deg/s^2
Roll	±21 deg	±20 deg	±30 deg/s	±500 deg/s^2
Yaw	±23 deg	±22 deg	±40 deg/s	±400 deg/s^2
Heave	±0.18 m (±7.1 in)	±0.18 m (±7.1 in)	±0.30 m/s (±11.8 in/s)	+0.5 g
Surge	±0.27 m (±10.6 in)	±0.25 m (±9.8 in)	±0.50 m/s (±19.7 in/s)	±0.6 g
Sway	±0.26 m (±10.2 in)	±0.25 m (±9.8 in)	±0.50 m/s (±19.7 in/s)	±0.6 g

Sensors

Three accelerometers were mounted on the platform, making a three-dimensional array. Measuring directions were set up according to the initial position of the testing individual: Front-Back (North-South), Side-Side (East-West) and Up-Down. The accelerometers used in test had sensitivity of 0.005 g and a measuring range of ±2g; sampling rate was set to 200 Hz. A smart bracelet was used to monitor heart rate on the individual's wrist. It was connected to a smart phone via Bluetooth, to have control over the data collection. Every test was recorded and stored for posterior analysis. Sampling rate for this device was 1 Hz. Video recording was used to monitor testing subject and table motions. Table displacements were monitored using visual targets attach to the table. Human motions was monitored using multiple video set and a targetless tracking algorithm. Individual stability and anxiety was observed visually from videos and from inquiries to the testing subject.

Experimental Tests

The shaking test at Politecnico di Torino consisted of 14 men and 12 women subjected to two ground motions. A well detailed virtual reality setting has been applied to the testing site in order to illustrate an indoor and an outdoor environment. Despite Kinect sensor is able to record the displacements of several nodes of the human body, only the ones of the chest and the elbows are considered because the movements of other points like knees, hands, feet were too noisy and not representative of the behavior of the tested individuals. The results were divided according to the gender only. Other classifications, like the age, the health condition, or the height were not considered because the size of the tested individuals does not allow further classifications. Each person has been equipped with safety devices (helmet, harness, pads for knees, elbows and wrists) and a virtual reality viewer (Fig. 5).

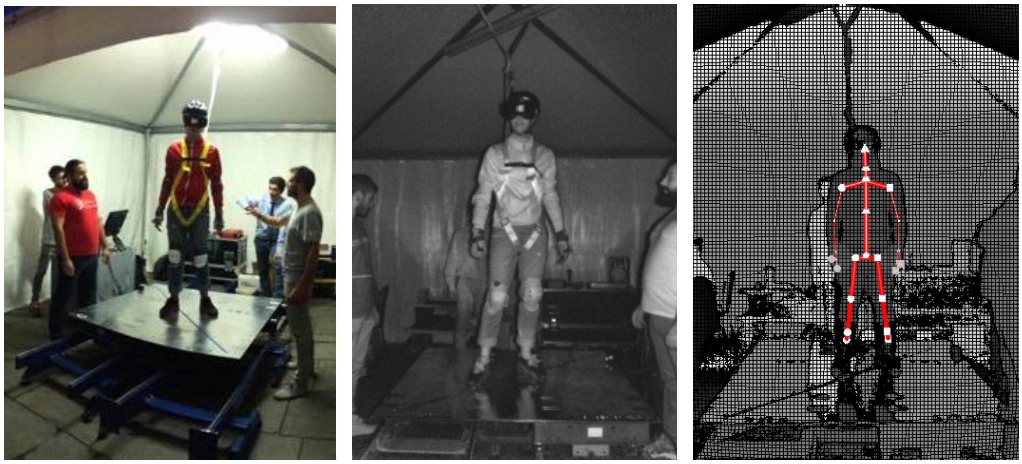
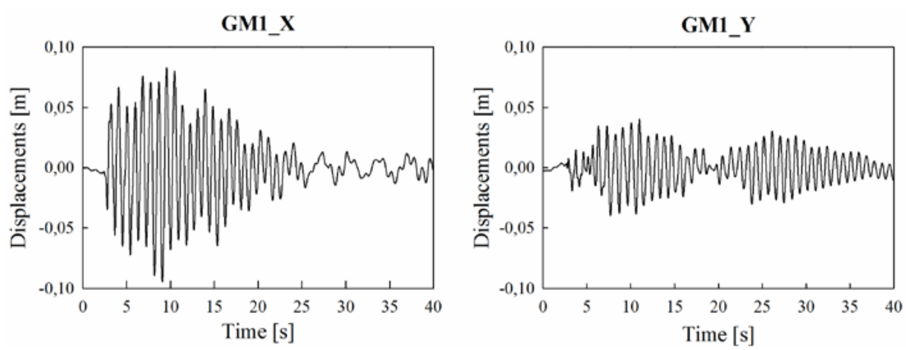


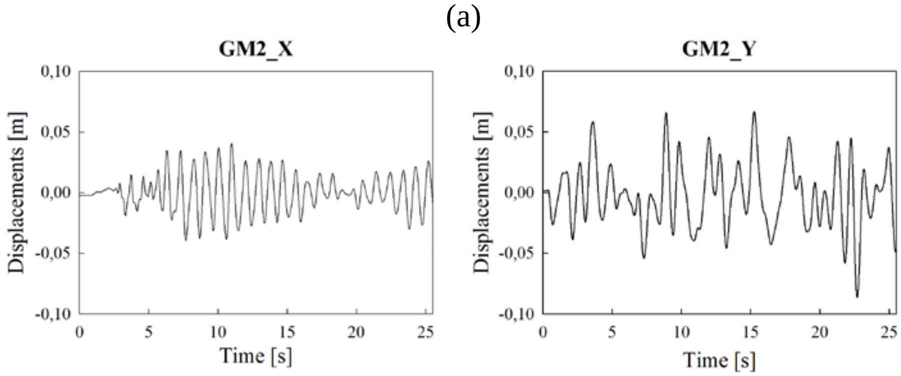
Figure 5. Tests performed at Politecnico di Torino.

Ground Motions

Two seismic signals are used to simulate the shaking table motion. They were applied one after the other for each individual with a ten-second interval in between in which the platform is motionless. The signals were presented in terms of displacement as the control system requires displacement input for its operation and they are different along x and y directions. The first ground motion is based on the 2014 South Napa earthquake in San Francisco at the 62nd floor of a residential building (Fig. 6a). The second is a white noise (an artificial frequency-rich signal) with a frequency range between 1 and 5 Hz (Fig. 6b). The magnitude of the displacements was scaled in order to be adequate to the available safety equipment to avoid injuries.



(a)



(b)

Figure 6. Displacement time histories used in the first (a) and second simulations (b).

Test Results

Figs. 7 and 8 show a comparison between men and women about the time history vertical displacements of the chest and the left elbow during the first and second ground motions, respectively. The time history in each graph is obtained as the average of all the single time histories recorded for the tested individual (man or woman) calculated at each time step (30 ms). Moreover, the recorded signals have been normalized with respect to the starting point at rest and the movements of the elbows have been connected to the chest's ones by subtracting the chest's position at every time step. Results for right elbow are quite similar to the ones for left elbow, thus they are not reported. It was notable that, during the test, almost every individual tried to improve her stability by rising her arms as well as by lowering the center of mass. This is supported by the results in Fig. 7 where the chest movement is always negative (towards the ground) while the elbow movement is positive as everyone was observed to rise his arms during the shaking. Comparing men and women it is possible to see how the first tend to stay more in a lower position and to rise the arms less than the women. Fig. 8 shows instead the results for the second ground motion. Overall the displacements are smaller both because the second signal has a lower intensity and people got used to the shaking. In fact, there are even displacements of the elbows downwards, as when the second shake starts people already hold their arms up.

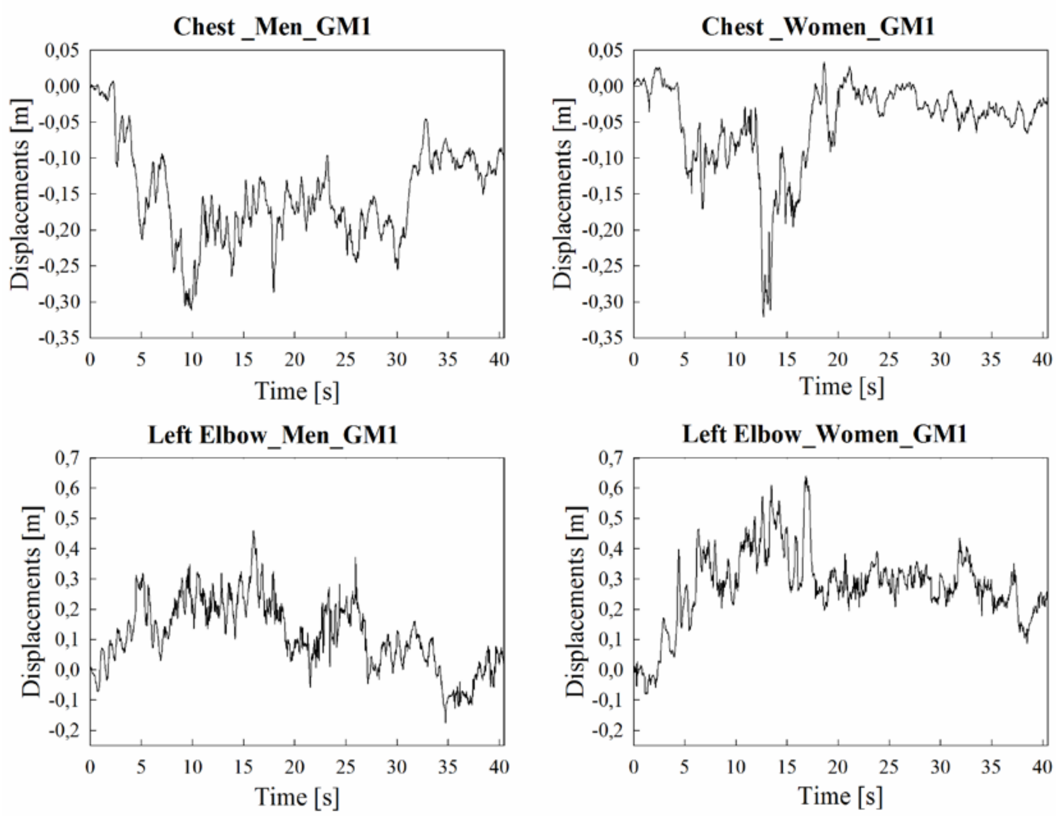


Figure 7. Displacements vs time of the control points for men and women during the first shake.

The experiment aims at assessing also the emotional aspect of the people. Therefore, all tested individuals were observed during and after the test by a designated person who assessed each individual based on five criteria: capability to step down from the table, capability to walk, facial appearance, capability to speak, excitement. Each person has been given a score between 1 and 5 for each of the five criteria, where “1” means a non-natural behavior and “5” means a natural behavior, as in the case of no earthquake. This has been done by observing their behavior during the test and the way they walked and spoke after the test. The average of this evaluation is presented in Table 2 distinguishing again between men and women. It is clear that almost all people behaved quite well in all assessments as the average value for each criterion ranges between 4 and 5. This means that the individuals were not much affected emotionally by the shaking, as they had expected the shaking before it started.

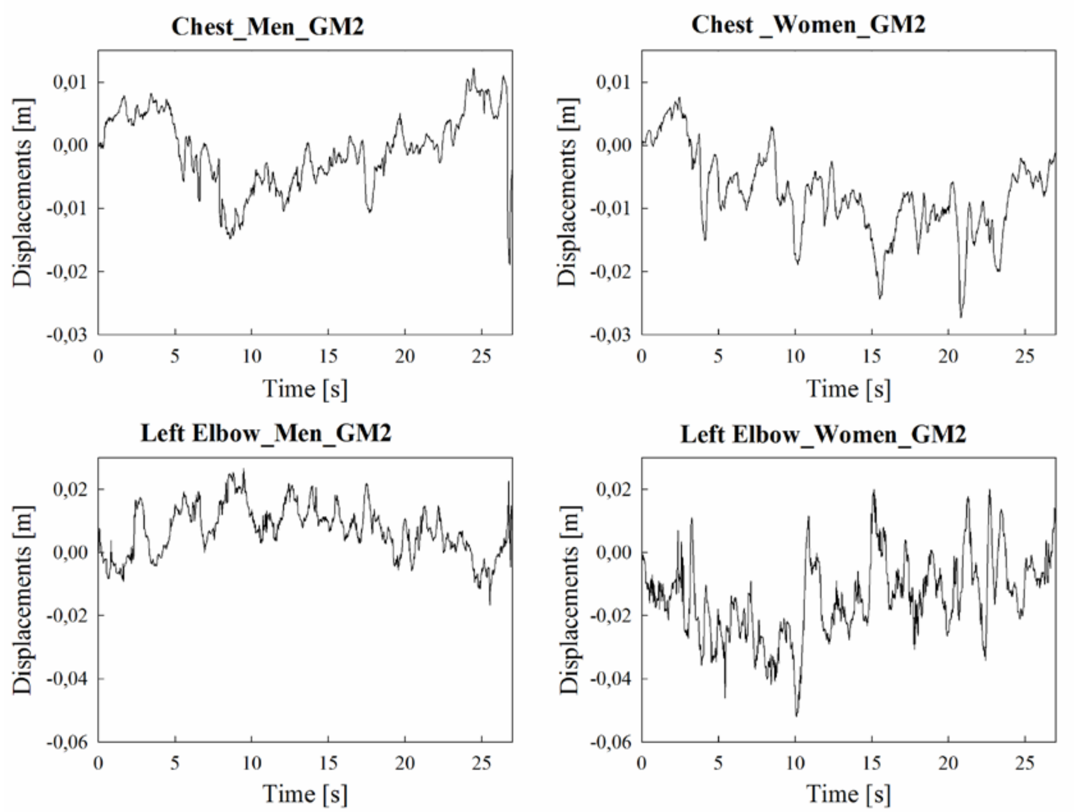


Figure 8.   Displacements vs time of the control points for men and women during the second shake.

Table 2. Average assessment of the tested people’s motor skills and emotions.

	Capability to step down from the table	**Capability to walk**	**Facial appearance**	**Capability to speak**	**Excitement**
Men	4.56	4.56	4.00	4.67	4.56
Women	4.33	4.17	4.00	4.67	4.33

The test at University of Chile was performed on three individual ages: 55, 29 and 25, two males, one female. Male weights were approximately 800 N and female weight 550 N. Testing position was standing with the possibility of walking during testing. Some of the tests were performed using and eye cover to reproduce full blackout during shaking (Fig. 9).

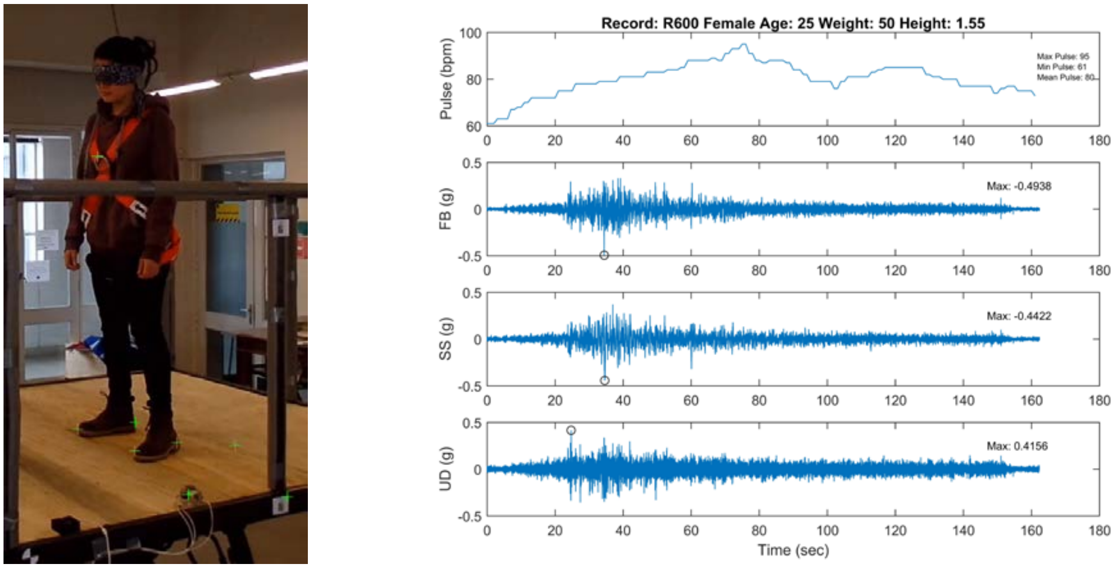


Figure 9. Sample 1 – University of Chile.

In Fig. 9 it is presented (on the top right) the pulse rate for a female testing individual. The motion, as recorded on the table, is presented on the bottom right three figures, indicating the initial orientation of the individual with respect to the axes of motion (FB: Front Back, SS Side to Side and UD vertical). As expected different results are obtained from each individual. The use of long duration records observed in large magnitude earthquake show an important difference in the tested individual. The arrival of P wave alerted the induvial of a possible incoming earthquake motion. The Chilean tested individuals are generally used to this feeling so they got prepared for the possibility of strong motions. The long duration, with relative few large velocity pulses, generates a state of alert and anxiety. Body motions were limited and concentration was dedicated to maintain the standing position. The video tracking, green cross in Fig. 9, show the initial balancing and later feet motions to maintain vertical stability.

Several shortcomings were observed to get reliable responses. With respect to motion tracking the need for several cameras so the motion of the induvial along the table is detected. The cameras can be synchronized by internal software but the best option is to track an initial sharp sound and a common target on the table. The best way to track emotion is by questionaries rather than sensors in the body, that generally detect reactions later event occurred. The individual rapidly got use to the motion. So emotions start to be control if several sequential events were input. This is a good indication that training individual in critical decision positions can be trained so they can react more appropriate at least base on their emotions. The effect of vertical and rotational event is important nevertheless few records exist for vertical motions inside structures, and rotational motions are non-existent. Motions inside structure and especially in tall building are long durations with large displacement. This requires large stroke and velocity for the testing facilities.

The critical issues detected at this stage of the research are: the position of the individuals; the previous experience in strong shaking; the needed reaction on during the motions, especially if the individual has to perform critical task during the event; the seismic motion duration; frequency content; frequency evolution; presence of large velocity and displacement pulses and the distance between initial P wave alerting signals and strong motion shaking.

Conclusions

Individual response is highly dependent on expectations, experience and mental preparation. In Chile due to its high rate of seismicity, with a magnitude 5 earthquakes, or higher, occurring in average 70 times per year in the country, people are more trained to react to strong ground motions. Individuals were tested for several different motions and they learned quickly how to reposition themselves on more stable position. When the individual experiences loss of equilibrium, the first reaction observed is to lift and open the arms and to lower the body's centre of gravity for ensuring equilibrium. It has been observed that the surprise component affects essentially the outcomes. Long ground and floor motions produce higher anxiety but not necessarily uncontrollable stability. The use of special tools as virtual reality and multi-degree of freedom platforms allows to reproduce more consistent conditions. These experimental observations on shaking table facilities enable the development of further human behaviour models.

Acknowledgements

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